westward toward the continent to the position on the morning of the 9th. Such a movement is not impossible, but to suppose it to have occurred is to trespass too much on the notes of interrogation that are marked opposite the positions 8*a*. and 8*p*. If we suppose that the high clouds seen in St. Croix down to noon on the 10th moving from east-northeast came from as far away as from the position 9*a*., we assume that they came from about 1,200 miles away, which is perhaps an extreme supposition, yet seems likely when compared with other cases.

A remarkable feature of the above case is that so shallow a depression (at the position 9*a*. the barometer reading is noted as 29.82) should have apparently been able to make its influence over the high clouds felt for so great a distance.

To this it may be answered that the apparent relation between the cyclone and the high clouds is perhaps merely accidental since another depression shown on the same Chart III does not show in the table any corresponding movements of the high clouds at St. Croix. This is true. The depression referred to moved past the west end of Cuba on the 27th, passed over Florida on the 28th, and on the afternoon of that day passed very near the position marked 9*a* of the previous depression (barometer 29.68—therefore, much lower than in the preceding case, yet no effects are shown in St. Croix). Referring to the table, however, we find that *no high clouds at all* were observed at St. Croix on the four days from the 27th to the 30th, consequently it is impossible to say whether the high air was affected or not by the depression then moving along the coasts of the Southern and Eastern States at that time. The writer, turning to his notes for those days, finds on the 27th "No cirrus down to 2 p. m., nor later," and on each of the three following days the words "No cirrus." It was, therefore, not for want of attention that no high clouds were observed on those days. Such gaps, however, are not altogether unknown, even when there is good reason to think that a cyclone is passing, and there must, of course, be a reason, though, as in many other matters touching the weather, it may be hard to find.

Reviewing the last hurricane season's observations of the high cloud movements here in St. Croix we may perhaps say that they seem greatly to strengthen the theory of the cyclone-cirrus relation stated in the writer's former papers on this subject. On the other hand, from a practical point of view, it must be admitted that the failure of the high cloud movements here on the 25th of September to indicate the true position of the center of the approaching storm, and the tardiness of the indications, both in that case and in the first storm of the same month, show that, useful though they may be, we can not rely mainly on such indications, but must still look chiefly to our old guides, the barometer and the movements of the lower air.

## METHODS AND APPARATUS FOR THE OBSERVATION AND STUDY OF EVAPORATION.

By C. F. MARVIN, Professor of Meteorology. Dated June 15, 1909.

### I.—METHODS.

The splendid campaign of work on evaporation of water from lakes and reservoirs recently undertaken by the Weather Bureau, under the immediate supervision of Prof. Frank H. Bigelow, promises to greatly advance our knowledge of this complex and highly important phenomenon. The essential details of the undertaking and some of the results of preliminary observations have already been more or less fully presented by Professor Bigelow in a number of papers published in the MONTHLY WEATHER REVIEW.[1]

Incidental to the inauguration of the work the writer has been called upon to aid in supplying much of the instrumental equipment required for making the desired observations. It was apparent at the outset that the ordinary markets for scientific apparatus are not prepared to supply any sort of well-designed standard apparatus for the observation of evaporation, and it became a practical necessity to develop and improve upon methods and apparatus previously employed, or to invent new devices of a character easily standardized and manufactured.

In order to reach satisfactory results along these lines it was necessary to carefully examine the whole problem of evaporation in order to learn what sort of apparatus and methods are really essential and to acquire that broad and full understanding of the subject without which the best results are impossible.

The object of the present paper is to give as briefly as is consistent with a clear presentation, what seems to the writer to be the real essence of the matter and to state his conclusions as to methods and apparatus that seem likely to lead to the most useful and accurate results. It is impossible, except in a few cases, to give credit to many other workers before me in this same field, but I am glad to be able to refer the reader who likes to go to the original sources, to the excellent annotated bibliography of evaporation by Mrs. G. J. Livingston.[2]

#### STATEMENT OF THE PROBLEM.

A great amount of labor and study have already been expended upon the observation and measurement of evaporation by students of agriculture and plant physiology, by engineers, meteorologists, and others, but the results fail to agree, nor can we reconcile the discordances in any satisfactory way. We must, however, recognize that the separate contributions are not necessarily erroneous or inaccurate, but rather that they are solutions of only a part of a large and very complex problem that often has been but imperfectly appreciated and comprehended, and that has not as yet been fully analyzed and solved.

Evaporation, to the engineer interested in great problems of irrigation and the conservation of water supply, means evaporation from large surfaces of water, such as lakes, reservoirs, rivers, ditches, etc. The agriculturist, however, is interested perhaps only in the evaporation from the moistened surface layers of the ground under different conditions of cultivation and treatment, whereas the plant physiologist wants to know about the evaporation from the blades of grass and all sorts of growing vegetation. Another class of engineers wants to know the laws and amounts of evaporation going on under the artificial but none the less definite and important conditions that obtain in drying kilns, curing houses, cooling towers, etc. It seems almost necessary to apologize for emphasizing the fact that each of these constitute a separate and distinct phase of the great general subject, and each requires and must receive separate and special study appropriate to the peculiar conditions. Nevertheless I feel compelled to mention this seemingly obvious fact because I find the problem is often most vaguely and narrowly comprehended even by some who profess to be students of the subject.

We must recognize, therefore, that in the arts and in nature the phenomena of evaporation are going on under a great variety of conditions, so different in fact as to constitute several distinct classes, and that a result, or a form of apparatus that may be entirely sufficient and satisfactory in one class may be of little or no value in another.

In this statement of the general problem it seems necessary to emphasize another seemingly simple and obvious truth, viz, that instrumentally it is a very easy thing to measure evaporation under certain definite and prescribed conditions, but it

[1] See Studies on the evaporation of water from lakes and reservoirs. Monthly Weather Review, July, 1907, February, 1908, Annual Summary, 1908.

[2] Monthly Weather Review, June, September, November, 1908; February, March, April, May, 1909.

is a very difficult thing to correlate the observed evaporation under one condition with that under another. I have been repeatedly urged to invent an instrument to measure evaporation, but in almost every case I have found that the information really desired by the party making the appeal was not how to *measure* evaporation, but how to *correlate* the observed amount under one specific condition with that under another condition.

The evaporation from a cup of water or from a large pan or from a large mass of isolated, damp soil, or from the damp surface of a piece of paper or a porous cup, can each be individually measured with comparative ease and accuracy. When we have these measures, however, we find ourselves confronted by a far more difficult problem, viz: How can we pass from the evaporation observed to take place from a pan to the evaporation from the surface of a large lake or reservoir? How can we find the evaporation from the leaves of plants and growing vegetation, and from the cultivated and uncultivated fields, and from the blanket of snow that covers the ground in winter? And what about the evaporation in kilns, curing houses, dryers, cooling towers, etc? The answers to these several questions can be reached only after having carefully worked out the law of correlation between the evaporation under conditions where it can be measured and which simulate as nearly as may be the conditions under which the evaporation is desired.

The engineer seeking the evaporation from lakes and reservoirs will probably find measurements from pans of water best suited to his needs, whereas the evaporation from moistened disks of paper or porous cups probably best represent the phenomena of transpiration in growing vegetation. Each class of phenomena must be studied on its own merits. The great problem lies in the working out of a correlation; it is not so much a problem of apparatus or of observation.

Thus far we have thought only of evaporation in a given location, where the water supply is actually present. The engineer often desires the answer to yet a different sort of question, viz: "If I build a large reservoir in a given location what will be the loss by evaporation?" This question can not be answered at all at the present time because we do not even know the loss by evaporation from reservoirs already in existence. When this latter has been determined and correlated with the existing meteorological conditions the answer to the other will depend upon what we know of the climatic conditions at the site of the proposed reservoir, and to what extent we can predict how much the building of the reservoir will modify, if at all, the climate of that site and what will be the temperature of the water surface. When the laws of evaporation from existing water surfaces have been satisfactorily formulated it will be a simple matter to estimate, with fair accuracy at least, the evaporation from a proposed reservoir in a climate of known elements.

Having now differentiated the several aspects of the general problem we shall next take up in some detail the question of method and apparatus; but we can not treat the whole subject at this time and we therefore propose to limit ourselves to a consideration of the evaporation from free water surfaces only, such as lakes, reservoirs, etc., having in mind the bearing of this evaporation upon great engineering projects in the interests of irrigation and the control and conservation of water supplies.

## CUSTOMARY METHODS AND THEIR FAILINGS.

Engineers seeking to measure the loss of water from a large reservoir or similar body of water have long been accustomed to measure the evaporation from a single pan of water floating in the lake. Sometimes more pans than one have been observed. The pans are not always floated, but sometimes are located on the banks or buried in the soil and otherwise variously exposed. Data obtained in this way do not give us the evaporation from the lake for two different reasons.

(1) The evaporation from the pan is not likely to be the same as the evaporation from the lake, even in the immediate vicinity of the pan, because the temperature of the water in the pan and the effects from other meteorological conditions such as wind, humidity, etc., are quite certain to differ more or less in the two cases. These differences may be small in the case of floating pans, but they are likely to be too large to neglect, especially in the case of pans otherwise exposed. Briefly, therefore, a certain correction or reduction is necessary to enable us to pass from the observed evaporation in a pan to the estimated evaporation from a free water surface in the immediate vicinity.

(2) Even if we can apply this correction to our observation and thus find the evaporation from the lake or reservoir in the given locality, we are not at all justified in assuming that the evaporation is the same over the whole exposed surface. There are many reasons why the evaporation should differ from point to point, especially in arid and semiarid, windy regions, where evaporation is very active. To windward the loss of water is greatest unless high sheltering banks cut off the free access of dry winds, and the amount falls off rapidly as the air moves over the water and itself becomes charged with moisture, thereby lessening the evaporation from the surface over which it subsequently passes.

### *Integration of evaporation.*

The rate of evaporation over a large water surface in dry, windy regions is therefore very unequal and the total loss of water can be ascertained only by some sort of summation or integration of the variable amounts.[3] How this may be worked out is indicated by the graphical method of integration described below.

Let fig. 1 represent an outline or map of the body of water whose evaporation is under study. Suppose the evaporation has been measured at numerous points more or less uniformly distributed over the surface, as, for example, by the aid of

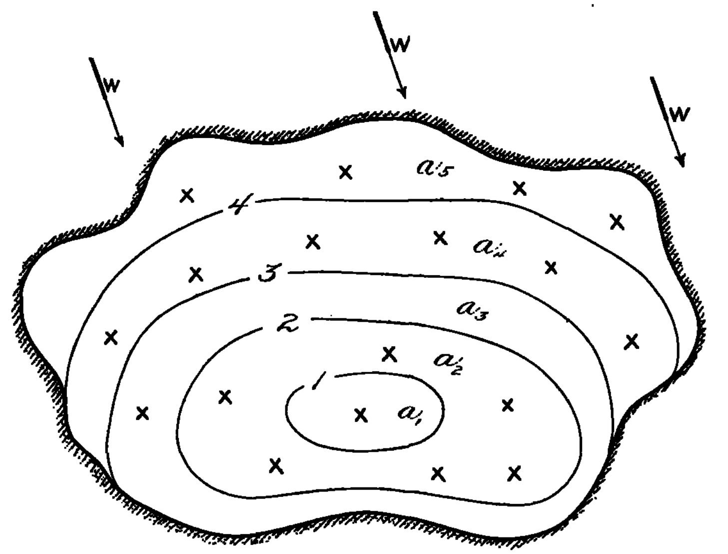


FIG. 1.—Diagramatic integration of evaporation.

floating pans. If the amounts of these evaporations are plotted on the map then we can draw such lines of equal evaporation or "*isothymes*,"[4] as are indicated by 1, 2, 3, etc., in fig. 1. The inter-relation and configuration of these lines will no doubt have a more or less definite relation to the amount and direction of

[3] In a few exceptional cases it may be possible to accurately measure the inflow, outflow, and seepage of a sea or reservoir; then, of course, evaporation = inflow — outflow and seepage.

[4] Mr. C. Fitzhugh Talman has kindly called my attention to the fact that Aristotle has used the word "*thymiasis*" in nearly the same sense as our word evaporation, and it therefore seems that such combinations as "*isothymal*," "*isothymes*," etc., are justified by this ancient usage.

wind movement, the form and extent of the water surface, the topography of the environment, etc. Let the areas between the several "isothymes" be ascertained and designated by $a_1$, $a_2$, $a_3$, etc., and let $A$ = total area of the water surface. Now we may reasonably assume that the average evaporation over the area $a_1$ is the mean of the observations that fall within that area. For the areas $a_2$, $a_3$, etc., it will be sufficient doubtless to take the mean of the "isothymal" lines bounding the respective areas. Let these several average amounts of evaporation be represented by $E_1$, $E_2$, etc. It now plainly follows that the total loss from the whole surface is given by the equation

$$E = \frac{a_1E_1 + a_2E_2 + a_3E_3 + \quad . \quad . \quad . \quad a_nE_n}{A} \quad \ldots\ldots\ldots (1)$$

Obviously this method, with a large number of observations carefully plotted, gives the result sought for with great accuracy. How serious the error may be when only one or a few observations are used, can not be told until the process here indicated has been systematically applied and at least some data obtained to show how much the evaporation differs from place to place over an extended water body under different conditions. This important method of analyzing the problem has not been followed out to any definite result so far as I know. Apparently a systematic study of the amount of variation in evaporation over large surfaces of water subjected to widely different atmospheric surroundings, constitutes a first step to the solution of the problem in hand. No matter how carefully or how accurately the evaporation is measured from a floating pan or one exposed in any other manner, it will never be possible to calculate the loss of water from a large lake until we have definite data upon which we can lay out a map of the distribution of the evaporation over the surface.

*The evaporation equation.*

It is almost futile to strive, as is often done, to so dispose a pan of water by floating it, for example, that its whole environment shall be *identical* with that of the water in a lake. Whether we use a large or small pan, and float it in the water or on a raft, or expose it otherwise, the water temperatures are always more or less different; and do what we may the action of the wind on the free water surface is very different from its effect on the water in the pan, so we are compelled in any case to take account of greater or less differences in environment between the water in the pans where we can measure the evaporation and the water of the body whose evaporation is desired. Now to enable us to take account of these differences we must have an evaporation equation which expresses the influences the surrounding conditions exert on the evaporation and when we have this equation it is then no longer necessary to confine ourselves to some particular kind of evaporation apparatus exposed perhaps in some manner that renders observation and maintenance troublesome, inconvenient, and difficult, but we can, instead, avail ourselves of more simple and convenient apparatus easily observed and maintained.

Various attempts have been made to formulate such an equation as now required, but these differ not only in form, but especially in the value of the several supposed constant terms, so that when they are applied to one and the same case very different amounts of evaporation are indicated. The equations fall sharply into two classes: (1) Those developed from the mathematical and thermodynamic equations representing the phenomena of pure diffusion; (2) partly rational and partly empirical equations that aim to express the relation between the measured evaporation and all the meteorological conditions by which it is influenced.

*Evaporation by pure diffusion.*—Lord Kelvin[5] applies the general equations of pure diffusion to a large number of practical everyday problems and points out in the case of the diffusion of carbon dioxide through air that the results prove that its approximately uniform distribution is due to convection not to diffusion. The same is true of water vapor. Stefan and others have endeavored to develop equations for evaporation based upon pure diffusion, but the fundamental simple assumptions essential to the mathematical treatment of the problem are highly artificial and do not represent any real conditions that actually arise in nature.

The writer has just completed a very careful series of measurements of evaporation of water from a 50-inch pan filled to the brim, exposed in a large room under conditions that approximate those of pure diffusion from a small source into a very large medium. Such evaporation is very slow. During twenty-three days the average rate was 0.00293 centimeters per hour. The least amount reported by Professor Bigelow at Reno, when the wind was estimated at 1½ to 2 kilometers per hour, was sixteen times greater than that here observed. On several days, with dry weather conditions prevailing outside, the air in the room at a point 2 feet above the pan contained scarcely any more water vapor than the general room air which on these occasions ranged from 35 to 50 per cent relative humidity. These observations were obtained by the use of a special hair hygrometer to be described later. The readings were constantly checked by sling psychrometer readings and are entirely reliable. The moisture contents of the air in the room rose and fell from day to day strictly in accord with the outside weather conditions, and the effects of the evaporation from the pan were scarcely observable, notwithstanding that pains were taken to avoid renewal of the room air by ventilation, etc. The whole evaporation by diffusion, even when aided by some convection and accidental air currents which we know must have existed, did not appreciably modify the moisture conditions of the general room air.

To still further demonstrate the extreme slowness of evaporation by diffusion, another experiment was made. A dish of water, 63 milimeters in diameter, was placed in an air-tight chamber having a capacity of about 1 cubic foot, with a hair hygrometer at the top. The experiment was started when the outside air had a humidity of 43 per cent. At the end of six hours the humidity at the top of the chamber had risen from 43 to 69 per cent. The subsequent rise of humidity was very slow, and saturation was not attained until after eight or nine days. Finally, the same experiment was repeated with a small electric fan running gently inside the chamber. Saturation was reached after 2¼ hours.

The difference between evaporation in still air by diffusion and that which occurs in nature when the air is stirred by even the most gentle zephyrs is very great, especially when the air is relatively dry or of low humidity, and this important fact must be incorporated in the evaporation equation.

*The Dalton equation.*—The equation which has been used by nearly all those who have made a study of evaporation is due to John Dalton, 1803. In stating the Dalton and other equations the following notation will be employed:

$\frac{dE}{dt}$ = depth of water evaporated in the interval of time $dt$.

$E_1$ = depth of water evaporated in one hour.

$e$ = general symbol representing vapor pressure.

$e_s$ = saturation vapor pressure at temperature of the water surface.

$e_a$ = saturation vapor pressure at the temperature of the air near (within a few feet of) the water.

$e_d$ = saturation vapor pressure at the temperature of the dew-point in the air near the water.

[5] Encyclopedia Britannica, 9th edition. Article, "*Heat.*"

$\frac{de}{ds}$ = expression representing the change of vapor pressure with temperature as signified by the term $S$ = temperature of the surface of the water. This quantity is merely the tabular difference in ordinary vapor pressure tables at the temperature under consideration.

$\tau_a$ = temperature of the air on the absolute scale.

$v$ = velocity of wind.

$B$ = barometric pressure,

$C$, $a$, etc = supposed constant terms.

The Dalton equation may be written as follows:

$$\frac{dE}{dt} = C(e_s - e_d)\,(1 + av) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Many careful writers on the theory of evaporation, including Dalton, have recognized the influence of air pressure on evaporation, and as early as 1789 Saussure directly compared the evaporation on an elevated mountain pass in the Alps with that under similar conditions at Geneva, where the air pressure was greater in the ratio of nearly 3 : 2. He found that the evaporation was over twice as great in the Alps. Those who have applied the Dalton equation to practical observations have sometimes ignored the pressure term even where the range of pressures comprised within the data has been considerable.

The following results quoted from Prof. F. H. Bigelow[6] give the evaporation in millimeters per hour for an assumed case of water temperature 23.9° C., dew-point temperature 15.6° C., wind velocity 10 meters per second (35.8 kilometers per hour). The values are computed by the Dalton equation, using the coefficients found by the several authorities cited:

Abbassia (Egypt), $E_1 = 0.1337$ millimeters... (3)
Fitzgerald (Boston, 1887), $E_1 = 0.2162$ millimeters... (4)
Carpenter (Fort Collins, 1887), $E_1 = 0.1504$ millimeters... (5)
Stelling (Russia, 1875, 1882), $E_1 = 0.3495$ millimeters... (6)

The present writer adds the following values from Bigelow's work at Reno, Nev., and Mecca and Indio, Cal.[7]:

Pan on ground, irrigated alfalfa field, Reno, Nev., $E_1 = 0.658$ millimeters .............. (7)

Pan on ground, partly irrigated field, Date Garden, Indio, Cal., $E_1 = 0.476$ millimeters.... .......... (8)

Pan on ground, Date Garden, Mecca, Cal., $E_1 = 0.438$ millimeters .............. (9)

Pan on ground, dry field, Indio, Cal., $E_1 = 0.261$ millimeters ............. (10)

The engineer may well be at a loss to choose between this widely discordant data, which testifies to the inexactness of our present knowledge of the subject.

Reno, Nev., is 4,500 feet above sea level, with an average air pressure at about 25.5 inches, whereas Mecca and Indio, Cal., are at or slightly below sea level. This condition may partly explain the seemingly great evaporation at Reno, Nev., but the effect of pressure on evaporation has been omitted by Bigelow in his discussion of these observations.

*The Weilenmann equation.*—Weilenmann[8] developed an equation with great care, which he proposed be used to compute the monthly and seasonal evaporation directly from the known meteorological elements. While we can not accept the numerical coefficients employed by Weilenmann, the form of equation developed by him is worthy of brief discussion.

Using the notation adopted above, his equation may be written as follows:

$$\frac{dE}{dt} = \frac{C}{\tau_a\left(\frac{de}{ds} + AB\right)}(e_a - e_d)(1 + aBv) \quad \ldots\ldots (11)$$

Although this resembles the Dalton equation (2), yet it presents notable differences. The pressure term $B$ not only comes in with the $C$ term, as has been customary with some writers, but it also modifies the wind coefficient $a$. The term $e_a$ will be the same as $e_s$ in (2) if we suppose the evaporating water and air have the same temperature. This was not so assumed, however, by Weilenmann. The equation also contains the term $\tau_a$ = the absolute temperature of the air and the term $\frac{de}{ds}$, in which latter feature the equation anticipates Professor Bigelow's use of this ratio. For purposes of comparison, we may write here the Bigelow equation, as follows:

$$\frac{dE}{dt} = C.\frac{e_s}{e_d}\cdot\frac{de}{ds}\cdot(1 + av) \quad \ldots\ldots\ldots\ldots (12)$$

Weilenmann explains that $\frac{de}{ds}$ must be taken for a temperature between the air temperature and the wet-bulb temperature and Bigelow takes $\frac{de}{ds}$ for the water surface temperatures. Now water evaporating freely in a pan will take on a temperature which will average below the air temperature but yet be warmer than the wet-bulb, so that this term in the two equations will be nearly the same, except that it stands in the denominator in one case and in the numerator in the other. The latter, i. e., the Bigelow usage, seems to be the more rational.

*Marvin equation.*—The foregoing appear to be the most noteworthy evaporation equations, but a number of other forms have been proposed. No one of them all will give zero evaporation under those conditions in nature under which we know from physical laws that the evaporation must be zero. Nor will any one of these equations, except the Dalton form give *negative evaporation*, i. e., show condensation which takes place every time the water temperature is less than the dew-point temperature. Negative evaporation was observed experimentally as early as 1750 by Richman and has since been repeatedly recognized by many other writers and doubtless by many observers of evaporation.

The present writer proposes[9] an evaporation equation of the following form:

$$\frac{dE}{dt} = \frac{C}{B}\,(e_a + e_s - 2e_d)\,.f(e)\,f(v) \quad \ldots\ldots\ldots (13)$$

In the absence of sufficiently complete observations of a suitable character it has not been possible to evaluate the constant factors or give the exact form of the terms depending on wind and atmospheric moisture. The new feature of this equation is the expression $(e_a + e_s - 2e_d)$. If we assume that the water and air are at the same temperature, as is nearly the case with the usual evaporation pans, then when this term is large or small, positive, negative, or zero the evaporation must be large or small, positive or negative, or zero. In these respects the equation gives consistent and rational results over the whole range of conditions which occur in nature and this is not equally true of any other equation that has thus far been proposed or used. The expression $(e_a + e_s - 2e_d)$ appears to indicate too much evaporation when the water temperature is considerably lower than the air temperature.

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[6] Monthly Weather Review, July, 1907, 35:313.

[7] Monthly Weather Review, Annual Summary, 1908, 36:442-3, computed by using the $C_d$ coefficients from Table 28 for pan 1, tower 4, viz, $C = \frac{1}{2}$ (0.073); Table 29 (wind 10-20), pan 1, viz, $C = \frac{1}{2}$ (0.0528), and $C = \frac{1}{2}$ (0.04860), also Abbe, Table 31, pan 4, viz, $C = \frac{1}{2}$ (0.029); the wind coefficient, = 0.0175.

[8] A. Weilenmann: Die Verdunstung des Wassers. Schweiz. met. Beobacht., 1877, 12:268-368. Reprinted, Zurich, 1877.

[9] C. F. Marvin: A proposed new formula for evaporation. Monthly Weather Review, February, 1909, 37:58, equation (6).

OBSERVATIONS MOST NEEDED.

Two classes of observations are essentially necessary before we can reach a satisfactory answer to the general question, "What is the amount of evaporation from an extended expanse of free water surface?"

I.

In order to establish all the details and evaluate all the numerical coefficients of the general evaporation equation we must have a large number of accurate measurements of evaporation under a wide range of atmospheric conditions, all of which must be carefully determined.

The observations must give us:

(1) The temperature of the water surface.
(2) The temperature of the air within a few feet of the water.
(3) The vapor pressure in the air near the water.
(4) The velocity of the air movement within a few inches of the water.
(5) The atmospheric pressure (within 1 or 2 per cent).
(6) The evaporation.
(7) Rainfall, condensation, etc.

The influence of salinity, impurity of the water, cleanliness of the surface, etc., are all fully recognized, but we hardly need consider these in the present paper.

There are many reasons why the great mass of existing data fails to supply our present needs. For example:

(*a*) Widely different methods and apparatus have been employed, yielding data which can not be definitely correlated.
(*b*) One or more important factors influencing evaporation are often omitted from the observations.
(*c*) Even if not actually omitted, one or more factors are often imperfectly determined.
(*d*) Faulty, irrational, and incomplete mathematical formulas are often employed to express the relations between conditions and effects.

The practice of multiplying *ad infinitum* great masses of data collected by faulty, incomplete, and inexact methods can not be too strongly condemned. Such observations do not reveal, but rather serve to obscure the real facts of nature. Reliance is placed upon elaborate methods of mathematical discussion and the sorely abused theories of probabilities, and it is imagined that grave errors of observation have been eliminated by the mere mass of data digested. It may fairly be said that 100 carefully made observations, each of which represents certain definite physical facts, are worth more than many thousand inexact, loosely related readings in which the errors of observation are mostly of a greater order of magnitude than the differential effects we seek to discover.

These considerations indicate how important it is, *first* to make only the best possible observations, *second* to subject all observational data to searching cross examinatian with a view to showing up its own inconsistencies, errors, etc.

*Wind observations.*—There are no less than six different and independent variables in the problem of evaporation and in nature practically all of these are wholly beyond our control. It is of the greatest importance, therefore, when collecting observations for a formula that the related data be determined accurately for short intervals of time during which the changes in the conditions may be minimized. This is particularly necessary with respect to the wind which often undergoes great changes in short intervals and in dry regions especially influences the evaporation very greatly. This consideration has led the writer to perfect a special form of apparatus which records simultaneously on the *same* sheet the wind and evaporation, including rainfall, if the evaporation pan is not sheltered against precipitation. This apparatus will be fully described in Part II, of this paper.

The diurnal march of air, water, and dew-point temperatures, as a rule, closely approximate simple harmonic curves, and while automatic records or frequent observations of these elements are of great value they are not so absolutely necessary as in the case of the wind. In dry climates even small changes in light winds produce large changes in the evaporation, whereas considerable changes in strong winds have relatively small differential effects. On the other hand when the atmosphere is already heavily ladened with water vapor both light and strong winds have relatively little influence upon the evaporation.

*Rain-sheltered pans.*—When rainfall occurs frequently and in considerable amounts it is practically impossible to accurately determine the evaporation if the rain is permitted to fall into the evaporation pan. In the writer's opinion the only plan to follow is to roof over the evaporation pan so that no rain can fall into the apparatus. This roof must not obstruct the perfectly free flow of the wind underneath. A pan so exposed will of course show a different march of temperature conditions, but the evaporation equation which will ultimately be developed will take complete account of this, and there are many very great advantages in the use of rain-sheltered pans. This plan has been recently put in operation by Mr. F. DeS. Willson on the Isthmian Canal Zone. Evaporation often goes on continuously during showers, as the air then is not necessarily saturated.

*Treatment of averages of variable conditions.*—Weilenmann, Stelling, Bigelow, and others who have attempted to calculate the evaporation for a long interval by using the *average* meteorological conditions for a day, for example, or a week or a month have uniformly disregarded an important mathematical consideration. If the wind, humidity, temperature, etc., remain constantly the same throughout a whole day, for example, we get a certain amount of evaporation. If, however, large changes occur in the conditions throughout the day it is quite certain a different amount of evaporation will result, even though the averages of the variable conditions are the same as the constant conditions. Stelling discovered in his computed results discrepancies exceeding 10 per cent for which he could find no explanation and which were doubtless caused by neglect of the point we are now discussing. Calculations based on averages must deal with the integral, not the arithmetical mean.

*Observations on towers, etc.*—Measurements from pans at different elevations above the ground and above water surfaces such as are now being made for the Weather Bureau under Professor Bigelow's direction give a number of interesting data, but only a part is useful in solving the great problem of evaporation. If the observations are made simultaneously at the different levels or are so arranged as to eliminate the effects of constantly changing conditions they give us:

(*a*) The vertical gradient of temperature of the air;
(*b*) The vertical gradient of vapor pressure in the air;
(*c*) The vertical gradient of wind velocity;
(*d*) The evaporation from pans of water exposed under these different atmospheric conditions.

The vapor pressure measurements at the different towers and levels may possibly serve to outline the form and indicate the different densities of the so-called vapor blanket that we imagine overlays large water surfaces. This filmy blanket, however, is utterly torn and disintegrated by the ordinary winds which change quickly and greatly, and are constantly intermixing variable amounts of new air and vapor with that of the blanket. It seems that any effort to outline and define this evanescent vapor blanket by means of the small number of observations thus far provided for is not likely to yield a real truth in nature.

The useful material obtained from the tower observations is the evaporation under different winds, temperatures, etc., all of which is of great value in establishing the coefficients of the evaporation equation. Observations of this nature can be obtained, however, quite as well by other methods of exposure.

*Laboratory experiments.*—Our inability to control in any way the several factors that influence evaporation in nature not only makes field investigations difficult and the results uncertain, but suggests the desirability of making such investigations by so-called laboratory methods. Fitzgerald's experiments on the effects of water temperature on evaporation are a notable contribution of this character. The writer is strongly in favor of a vigorous campaign on evaporation by laboratory methods. At the same time the great difficulty of producing and maintaining artificially all the desired conditions on a sufficiently large scale is recognized and constitutes quite as serious an obstacle to ultimate success as the difficulties encountered in field work.

II.

Yet a second class of observations is required in solving the question of evaporation from free water surfaces, viz, those necessary to bring out the laws of distribution of the variable evaporation over any considerable expanse of water. This has been fully explained in connection with fig. 1 and equation (1) above, but so far as known to the writer no systematic study of the problem has been attempted.

In the opinion of the writer, observations from pans floating in the water are almost the only data we can procure from which we may hope to be able to compute the true evaporation from an extended free water surface. The plan of calculating the evaporation from a few observations of temperature, wind, and vapor pressure is certain to prove crude and inaccurate unless the plan is carried out on a far more elaborate basis than is commonly expected. An observation of evaporation is a very definite and exact integration of a very subtile and highly variable phenomena. I think it is decidedly easier, more exact, and more scientific to actually *observe* the integrated result sought after than to try to compute a result from scanty observations upon several other phenomena to which the evaporation is indirectly related. The latter plan is only justified for crude results and when the more exact method is not available.

It has seemed worth while to bring out with some clearness all the general facts and principles presented in the foregoing because separately they will be found abundantly supported by the past literature of evaporation, but collectively they have not all been systematically and consistently regarded by each or any individual worker. No one may hope to formulate the true general laws of evaporation applicable anywhere and everywhere without paying careful regard to the lessons that are taught by the work and mistakes of others.

Section II of this paper will describe instrumental apparatus.

[*To be continued.*]

## A CHRONOLOGICAL OUTLINE OF THE HISTORY OF METEOROLOGY IN THE UNITED STATES OF NORTH AMERICA.

[*Continued from the Monthly Weather Review, March, 1909.*]

1851. E. E. Merriam, "The Sage of Brooklyn Heights," began the publication in the New York daily papers of a series of articles on "Heated terms and other weather phenomena." In 1853–1855 he frequently ventured on local weather forecasts, based in part on his own observations in Brooklyn, but largely on the telegraphic reports published daily in the newspapers.

1852. October. Date of Espy's fourth meteorological report, addressed to the Secretary of the Navy; called for by Congress July 24, 1854; referred to the Secretary of the Smithsonian Institution; ordered printed; published in 1857, with numerous notes which brought it up to the date of publication. This fourth report also reprints all of Espy's preceding reports.

1852. First edition of Arnold Guyot's collection of "Meteorological tables for Smithsonian Observers." A second edition appeared in 1857; a third edition in 1859; a fourth, or Libbey's edition, in 1884; a fifth, or Curtis's edition, in 1893; a sixth, or McAdie's edition, in 1896; a seventh, or third revised edition, in 1907.

1853. Meteorological stations established at grammar schools in Canada.

1853. Mr. Joseph Brooks, manager of a line of steamers between Boston and Portland, is said to have used the telegraph freely in obtaining information about the weather as affecting his navigation.

1853. Lieutenant M. F. Maury secures an International Meteorological Conference at Brussels, leading up to cooperation in marine work.

1853. William Ferrel (*b.* 1817, *d.* 1891) published a first popular article on the effect of the rotation of the earth on the winds and the ocean currents.

1853. November. James Henry Coffin (*b.* 1806, *d.* 1873) published his "Winds of the Northern Hemisphere" as a result of many years of work.

1853. Lorin Blodget published "On the Abnormal Atmospheric Movements of the United States," in the Proceedings A. A. A. S., 1853.

1854. Prof. Joseph Henry reported that the telegraph companies were furnishing the Smithsonian Institution with daily morning weather reports. He had suggested the custom, which became established, in accordance with which the first message each morning on opening any telegraph office was in answer to the salutation, "Good morning, what is the weather?" Each local operator gave to his division superintendent and the local newspapers a statement of these weather reports, viz, temperature, wind, and weather, and all of them were telegraphed to the Smithsonian Institution, where they were exhibited on a large wall map day after day during the years 1854–1861. These reports were frequently used by Professor Henry to predict or show the possibility of predicting storms and weather, a matter that he frequently urged on the attention of Congress. Espy and Henry were the prime movers in all matters of storm predictions both in this country and in Europe.

1855–1859. A series of five papers by Joseph Henry on "Meteorology in its Relations to Agriculture," published in the reports of the Commissioner of the Patent Office. They were reprinted (1886) by the Smithsonian Institution as Vol. II of Henry's Scientific Writings.

1856. Lieut. Silas Bent, U. S. N., initiates the Gulf Stream and Japan Current delusion.

1856. Espy invented his double nepheloscope and showed that expansion alone into a vacuum does not produce cloud or cooling since there is no work done by the expansion.

1857. Lorin Blodget (*b.* 1823, *d.* 1901), published his "Climatology of the United States."

1857. October 22–November 17, Espy ordered to transfer his work from the Smithsonian Institution to the U. S. Naval Observatory.

1857. William Barton Rogers (*b.* 1805, *d.* 1882), published in Silliman's Journal, a paper on the breaking up of a steady current of wind into an anticyclone on the right-hand side, and a cyclone on the left-hand side.

1858–1860. William Ferrel, published in the American Mathematical Monthly, a mathematical memoir on the motions of solids and of the atmosphere on the surface of the earth. This was followed eventually by his Meteorological Researches, Part I, 1875; Part II, 1878; and Part III, 1881; and by his joining the meteorological division of the U. S.